UNCLASSIFIED

UCRL-476

UNITED STATES ATOMIC ENERGY COMMISSION

GENERAL RECOMMENDATIONS FOR DESIGN OF SMALL CYCLOTRONS

by

Louis Wouters

October 21, 1949

University of California
Radiation Laboratory

Contract W-7405-Eng-48

Reproduced direct from copy
as submitted to this office

Technical Information Division, ORE, Oak Ridge, Tennessee
AEC, Oak Ridge, Tenn., 3-2-50--550-A20276

~~Printed in USA
PRICE 10 CENTS~~

copy # 15

UNCLASSIFIED

GENERAL RECOMMENDATIONS FOR DESIGN OF SMALL CYCLOTRONS

Louis Wouters

October 21, 1949

The remarks which follow describe in some detail the steps necessary in the design and fabrication of small cyclotrons. Magnet design and supply, tank design, the oscillator and early operational details are discussed and schematic drawings are appended.

Magnet Design

For most economical performance, it is of course desirable to operate the magnet iron near saturation; most soft irons begin saturating in the vicinity of 16 kilogauss, though some may be operated as high as 21 kilogauss. This figure, however, is not indicative of the field obtainable in the gap. In addition to the flux passing through the gap proper, this is caused by appreciable leakage flux around the periphery of the gap and around the coils themselves. Thus the additional flux causes the pole cores to start saturating well before the field in the gap proper reaches the saturation value. The amount of leakage flux depends on the gap proportions roughly in the following way:

Ratio $\frac{\text{Gap Height}}{\text{Gap Diameter}}$	Multiplying Factor	
1/2	2	
1/4	1.5	Region of small cyclotrons
1/10	1.2	

The required number of ampere-turns is calculated from the indicated formula on the Magnet Design Sheet, Table I, using the <u>total</u> gauss passing through the return yoke, that is, the field in the gap multiplied by this factor. It is also

A-1

assumed that the length of the pole cores and the distance from pole cores to return yokes is at least twice and preferably three times the gap height. Actually, in small cyclotrons, the required coil space necessitates dimensions such that these conditions are readily met.

As was implied above, saturation should preferably occur in the pole cores only; the return yoke must accordingly be designed so that its total cross sectional area is a good deal greater than that of the cores, say, at least 25 percent greater. It is important that the contact surfaces between yoke pieces and between yoke and pole cores be flush to eliminate additional air gaps. The pole core fastenings and coil fastenings should be compatible with the forces as calculated from the Design Sheet.

The coils should be wound so that they occupy approximately a rectangular cross section around the poles as shown in Fig. 1. Either too flat or too tall a coil intercepts more leakage flux and thus wastes turns.

The Design Sheet also provides formulae for calculation of coil resistance and heating. It is generally advisable to operate close-wound naturally air-cooled coils at a current density not exceeding 750 amps per square inch of conductor area. For intermittent operation this may be raised to 1000 amps per sq. in. If additional cooling is provided, as described below, this figure may be increased still further. Most coil designs favor large conductor areas and correspondingly high amperages; this reduces total voltage and simplifies both the insulation and the winding problems.

As an example of small magnet design, the 6-inch cyclotron shown in Fig. 2 has a yoke of area considerably greater than the core area; available standard mild steel bars dictated the indicated dimensions. The yoke frame is welded at the four corners; the cores are each held to the yokes by four long 3/4 in. bolts threaded directly into the core iron, which is 6 in. round stock.

The two coils were wound using available #13 D.S.C. wire, each coil consisting of three flat pancake windings of 1000 turns apiece, for a total of 6000 turns. Each pancake is 1 3/4 in. thick, 6 in. I.D. and 14 in. O.D., and is wound toroidally with a layer of .005 in. silk or empire cloth tape. These windings saturate the iron (~20 KG) at somewhat less than ten amperes; at this current the temperature becomes excessive in less than an hour.

Three coils are assembled onto the upper pole piece which is already in place on the yoke frame, with the lower pole piece removed. They can be held in place by insulated brass clamping bars bolted to the upper yoke piece. The other three coils are placed on the lower pole piece which is then slid into position and bolted down; similar coil clamping can be used.

Cooling plates could be inserted between each coil layer as well as on top and bottom of each coil assembly. These consist of flat donuts of 1/16 in. copper sheet, with a 6 in. I.D. cut-out and 15 in. O.D., having a 1/4 in. copper pipe soldered to the outer edges. During operation cold water is run through this set of pipes; together with a large fan for general circulation, such coils should operate steadily at 1300 amps per sq. in.

Summary of Initial Steps

1. Decide on desired pole gap and diameter.
2. Calculate required ampere turns taking into account leakage flux.
3. Decide on conductor size as dictated by available power supply or wire; depending on the type of cooling used, this fixes the operating current and, hence, the number of turns.
4. From geometrical considerations, design an approximately rectangular coil.
5. Design the magnet to fit around the gap and coils, leaving enough clearance between coils for accessibility to the tank in the gap. Check on flux leakage criteria as mentioned above.

It is well to go through these initial steps for several different designs.

Magnet Supply

For magnets of this size, a variety of supplies are available. Among the more convenient are the motor-generator set and the selenium-oxide rectifier unit.

The motor-generator set is most easily available since almost any d.c. arc welding outfit can be modified for this purpose. Current control should always be inserted in the field exciting winding. The magnet coil circuit must never be broken at high currents, of course, unless adequate surge protection is provided. This can consist of a thyrite resistor unit or an electrolytic tank of suitable size.

The selenium-oxide unit has no moving parts and will last almost indefinitely, but is more expensive. Current can be controlled by means of a variac installed in the a.c. power line.

The literature is replete with a variety of circuits for operating devices of this type and power rating.

Tank Design

In this size range, it is possible to use either glass or metal systems; the availability of reliable high speed pumps make the latter more attractive . The six-inch cyclotron tank as shown in Fig. 3 will be used as an example of a suitable arrangement of components.

The top and bottom of the vacuum chamber should be thin, circular steel plates (not much larger than the pole diameter), in order to decrease the magnetic gap as much as possible. To prevent field bypassing, the tank wall must be non-magnetic, preferably brass; the bottom plate is soldered to this wall. This is convenient from the standpoint of assembly of the other components. The top plate is sealed by means of a quite orthodox rubber seal.

The various operating elements are held in position and sealed through the tank wall by means of compression seals, a typical one being illustrated in the sketch in Fig. 3. The seal support pipes are soldered directly into holes in the tank wall.

The vacuum pump connection simply has a 1/2 in. glass pipe passing through the seal, opening into the tank. Evacuation is done progressively by a small mechanical pump, a mercury or oil diffusion pump, and a liquid air trap. Vacuum system techniques similar to those used in any physics laboratory are adequate here. An ionization gauge is the most flexible and reliable means of measuring high vacuum, and is sufficiently accurate. For low vacuum either a McLeod or Thermocouple gauge is used. For operation, a preliminary vacuum of about 10^{-5} mm hg should be attained; during "bakeout" pressure should not exceed $\sim 10^{-3}$ mm. Operation as a cyclotron can be attempted with a pressure of 10^{-4} mm or less with all r.f. and source power applied.

The ion source connection consists of a 1/2 in. pyrex tube passing through another compression seal for a distance of 1/4 inch into the tank. This provides insulation for two heavy (.060 in. to .100 in.) tungsten wires which enter through a press seal at the outer end of the glass tube. These wires are spaced by small ceramic (lavite) spacers; immediately beyond the glass tube the wires bend down and follow close to the tank bottom, to avoid interfering with the beam orbits. At the center of the tank, a filament is spot welded to these leads. In the past, an automobile headlight filament has been used, but the breakage has been high. A somewhat heavier wire seems appropriate, perhaps .025 in. tungsten. This filament rests on a small flat ceramic square which fits into the mica sheet as shown in the sketch; the latter is fastened to the tank bottom by means of a drop of sealing wax at the two corners <u>away</u> from the dee and filament. The hydrogen inlet is a small tubulation in the side of the glass tube; the hydrogen flow

can be controlled by means of a needle valve having a long tapering needle fitting into a long tapered seat. Alternative methods employ the leakage of gas past a loose fitting thread, the flow being controlled by the number of engaged threads of screw, or, as in the case of the 6-inch cyclotron, the use of a palladium metal valve, in which flow is controlled by the diffusion rate of hydrogen through thin electrically heated palladium. (These latter valves are possibly available from either General Electric or R.C.A.)

A .025 in. tungsten filament requires about 25 amps d.c. at a few volts for operation, which can be readily obtained, for instance, from a heavy duty battery charger floating across a storage battery. The storage battery acts as a very large filter condenser, being necessary to prevent violent vibration of the filament system which would result from unfiltered ripple. Current control is obtained by means of a series resistor. There must also be supplied the d.c. arc voltage and current, which appears as a negative bias between filament and tank ground. At normal operating pressures of 10^{-4} mm H_2, between 1/2 to 2 amps at 100 to 500 volts will be required.

The target connection is simply a 1/8 in. brass rod passing through a greased compression seal. The inner end is threaded, so that small metal targets may be mounted there.

The dee connection must be carefully insulated; this is accomplished by slipping a 1/4 in. pyrex tube completely over the 3/16 in. copper dee support rod from the dee edge to at least 2 inches beyond the seal. The compression seal then seals to this glass tube, and a separate seal is made at the outer end of the glass tube by slipping a short section of greased 3/16 in. rubber tubing over that end as shown in the sketch. The dee is six inches across and 1/4 inch high and is made of 1/32 in. copper sheet except for the edge strip which is

1/16 in. copper. In this unit, it is further supported by a 1/4 in. quartz stand-off under each corner. The r.f. dee voltage may be as high as 3 kv, which voltage is supplied by an oscillator such as that described in the next section.

The general tank arrangement need not follow the indicated layout; however, mechanical convenience requires more or less opposite placement of dee and ion source stems. It is also convenient to place the other seals to one side of the dee and source center line, so as to facilitate inserting the final tank assembly into the magnet gap.

An unusual feature is the "single-dee" construction; this has many advantages in simplifying tank and oscillator construction. The "other dee" is, of course, the tank proper. Better ion focussing can be obtained by installing a "dummy" grounded dee edge symmetric to the insulated dee, but this is a refinement which should be attempted only after the apparatus is operative.

The Oscillator

The accompanying circuit as shown in Fig. 4 has been employed successfully in this service; it is a grounded grid Hartley. We have found that the greatest problem with any oscillator circuit lies in confining the r.f. current to the desired paths. Neither a circuit nor a layout can show this realistically; however, it is easier to confine the r.f. currents to the diagrammed circuit in the case of the grounded-grid Hartley than in most other circuits. The dee-to-ground capacity appears as the major portion of the capacitance in the LC tank circuit, which must be calculated taking this into account; C^1 acts as a trimmer to adjust the frequency more precisely. A step-up in r.f. voltage is achieved by tapping down the plate connection. Note that neither side of the power supply can be grounded, the negative side rising up to the grid bias potential as the oscillator starts up.

In making the r.f. connections, it is important to provide short, broad

paths for current flow, especially in the ground circuits. A good design is to mount the tube through a large hole in a copper ground sheet such that this sheet is at the level of the grid terminal. The connection to that tube terminal can be simply a sturdy clip mounted directly on the edge of this ground sheet; the ground sheet can then extend up to the tank well. The coil, chokes and condensers may be grouped roughly as shown in the schematic layout in Fig. 5. While the tube should be placed as close to the tank as possible, it must yet be kept away from the magnetic field.

The radiofrequency voltage can be measured directly, if desired, by means of a V. T. Diode Voltmeter (employing, for instance, a high-voltage, high-vacuum diode made for the purpose) connected to the lead to the dee.

General Precautions

The voltages employed on the various cyclotron components are deadly; proper precautions must be taken, even during preliminary testing, to insure safety to personnel. Interlock switches on the power supply covers and grounding hooks in the vicinity of the cyclotron must be provided. A well-grounded copper screen box around the oscillator will help keep the r.f. from interfering with the other circuits.

The sample general circuit layout gives an idea of the space and electrical requirements. All circuits connected to tank elements should have adequate choking and bypassing to prevent r.f. from reaching the meters and supply lines. The operating controls and meters, especially those connected to magnet, source and r.f. power, should be readily adjustable and easily shut off, as by push button control circuits.

Prior to final tank assembly, preliminary washing of the parts in CCl_4 is recommended to remove organic matter. It is wise to avoid undue exposure to carbon tetrachloride vapor.

Operation

Assuming that all leaks have been successfully patched (glyptal may be used) and that a satisfactory base vacuum (10^{-5} mm) has been obtained, the next step is "baking-out." Radiofrequency power should be initially applied in short bursts, under reduced power (r.f. power control is conveniently obtained by means of a variac in the plate power supply). Glow discharges accompanied by large increases in tank pressure will be observed; r.f. power should never be left on for prolonged periods under these circumstances, else the risk is run of cracking the glass dee insulators. The power and length of application should be gradually increased until the vacuum remains less than 10^{-4} mm with r.f. on steadily at, perhaps 2 kv. If this cannot be easily attained, it may mean the presence of organic matter in the tank, such as grease, cutting oil, or rubber. Sometimes turning on the magnetic field will aid the baking out process.

The filament should now be turned on gradually, with the magnet on and r.f. off, and with perhaps 150 volts of arc bias applied. When thermionic emission starts, there will be some residual gas arcs, following which the arc voltage should be shut off until pressure returns to normal. The filament should be adjusted so that under high vacuum conditions, a moderate emission current (10-20 ma.) is observed with 200-300 volts arc bias. The r.f. power can now be turned on once again at reduced level, and the "baking-out" process repeated.

When a good vacuum (10^{-4} mm) exists with magnetic field and all power turned on, hydrogen may be admitted to the tank, "opening" the valve until the tank pressure rises by another 10^{-4} mm, meanwhile watching the arc current. (Depending on the type of valving employed, it may be necessary to first flush out any trapped air in the H_2 system.) The arc can be "struck" by carefully raising filament current or arc voltage -- an arc of 1/2 to 1 amp at 100 to 200 volts is usually satisfactory.

One can now start looking for a beam -- the radiofrequency and magnetic field are adjusted near resonance, and either one rocked back and forth until a current peak is indicated on the target probe. The probe may be pushed in closer to the center to facilitate locating this resonance. Then it may be withdrawn, meanwhile optimizing arc, filament and r.f. power by the beam current indication. The target probe must show a high resistance to ground; of course, a sensitive galvanometer (protected by r.f. chokes and bypasses) may be used initially for detecting the beam current, though it should be possible to obtain a few micro-amperes deflection on a standard 0-20 microampere meter. The six-inch cyclotron has indicated a 7 microampere beam, at a frequency corresponding to about 800 kv protons. It is often possible to obtain current readings due to ions reaching the probe by other than cyclotron paths. Thus, the authenticity of the beam should be checked by the sharpness of resonance as a function of r.f. tuning and magnet current, as well as by its sensitivity to hydrogen gas pressure. Background currents are generally quite insensitive, being "broad" in adjustment as compared to the true beam.

Of course, the final check lies in the detection of nuclear events resulting from the bombardment of the target by high energy protons. Suitable reactions for this purpose may be found in the light isotopes -- a convenient target substance would be LiF which, when bombarded with protons, will emit gammas from Li with .2 Mev threshold and from F with .3 Mev threshold. The target may be prepared by simply fusing a small amount of LiF onto a small stainless steel block mounted on the end of the probe.

The size of the machine depends on its purpose, of course. For educational applications a six to nine-inch pole piece is an economical range; for inducing light element reactions, it is probably worthwhile thinking of a somewhat larger machine, say, 12 to 15 inches, so that at least enough energy is available for

some neutron yielding reactions. In this size, the economics of magnet construction require "tighter" design than has been set forth here. Since more space is available, somewhat fancier tank construction also becomes possible.

This description of design and operation is meant to be a guide. Individual cases will no doubt require their own variations from this pattern.

Information Division
scb/10-24-49

TABLE I

Magnet Design Data

	Annealed Copper	99.98% Silver
Modulus of Elasticity - $\frac{\text{lbs.}}{(\text{inch})^2}$	17.5×10^6	11.5×10^6
Specific Weight - $\frac{\text{lbs.}}{(\text{inch})^3}$	0.322	0.380
Resistivity at 20° C - Ohm-Inches	0.679×10^{-6}	0.641×10^{-6}
Resistivity at 40° C - Ohm-Inches	0.732×10^{-6}	0.690×10^{-6}
Heat Conductivity at 20° C - $\frac{\text{Watts}}{\text{Inches } ^\circ\text{C}}$	9.76	10.52
Specific Heat at 20° C - $\frac{\text{Watt-Seconds}}{\text{lbs. } ^\circ\text{C}}$	174.9	105.9
°C Lin. Coeff. of Thermal Expansion	16.8×10^{-6}	18.8×10^{-6}

Formulas Independent of Material

Ampere-Turns = 2.02 x gauss x inches gap

Lbs. force on conductor = 1/1750 x kilogauss x amperes x inches length

Lbs. force between pole faces = 1/1.735 (kilogauss)^2 x (inches^2 area)

Formulas for Copper and Silver at 40° C Mean Temperature

$$\text{Kilowatt-Tons} = \left.\begin{matrix}(0.118)\text{Cu}\\(0.131)\text{Ag}\end{matrix}\right\rangle (\text{Mega-ampere turns})^2\,(\text{inches mean turn length})^2$$

$$\frac{\text{Amps}}{\text{Inches}^2} = \left.\begin{matrix}(469)\text{Cu}\\(525)\text{Ag}\end{matrix}\right\rangle \sqrt{\frac{\text{Kilowatts}}{\text{Tons}}}$$

$$\text{Inches}^2 \text{ conductor area} = \left.\begin{matrix}(2.130)\text{Cu}\\(1.903)\text{Ag}\end{matrix}\right\rangle \frac{\sqrt{(\text{Kilowatts})\,(\text{Tons})}}{(\text{Volts})\,(\text{Parallel paths})}$$

$$\text{Inches}^2 \text{ conductor area} = \left.\begin{matrix}(0.731)\text{Cu}\\(0.689)\text{Ag}\end{matrix}\right\rangle \frac{(\text{Mega-ampere turns})(\text{In. mean turn length})}{(\text{Volts})\,(\text{Parallel paths})}$$

TABLE I (Cont.)

Formulas for a Rectangular Conductor Losing Heat from Two Edges

(40° C Mean Temperature)

$$\begin{matrix}{}^\circ\text{C heating at center} \\ \text{of conductor}\end{matrix} = \left.\begin{matrix}(.00940)\text{Cu} \\ (.00821)\text{Ag}\end{matrix}\right\rangle 10^{-6}\ (\text{Inches width of conductor})^2 \left(\frac{\text{Amperes}}{\text{Inches}^2}\right)^2$$

$$\frac{\text{Watts}}{\text{Inches}^2\ \text{edge surface}} = \left.\begin{matrix}(0.366)\text{Cu} \\ (0.345)\text{Ag}\end{matrix}\right\rangle 10^{-6}\ (\text{Inches width of conductor}) \left(\frac{\text{Amperes}}{\text{Inches}^2}\right)^2$$

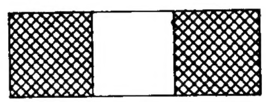
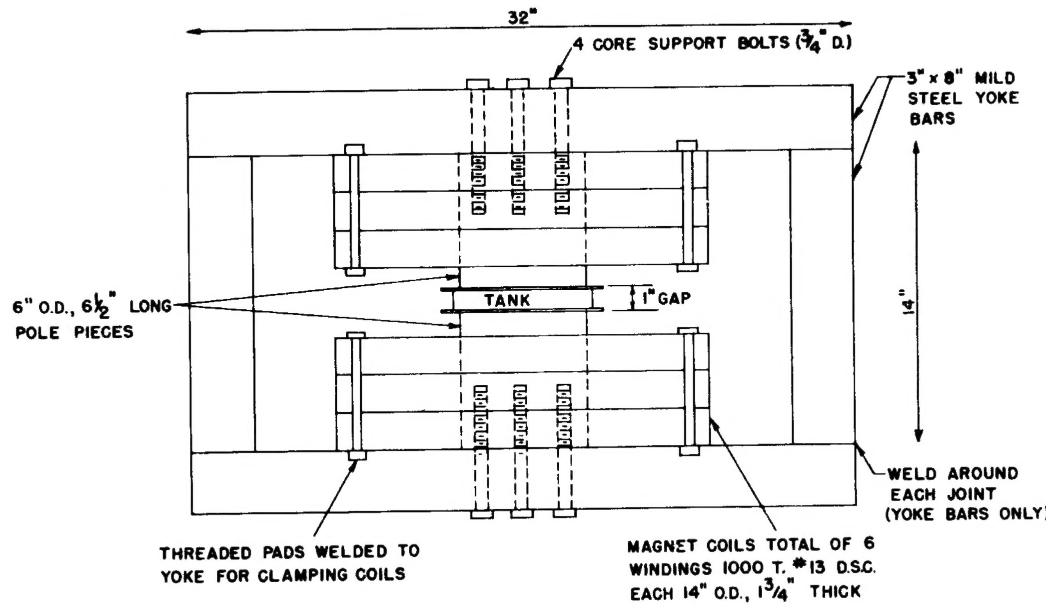


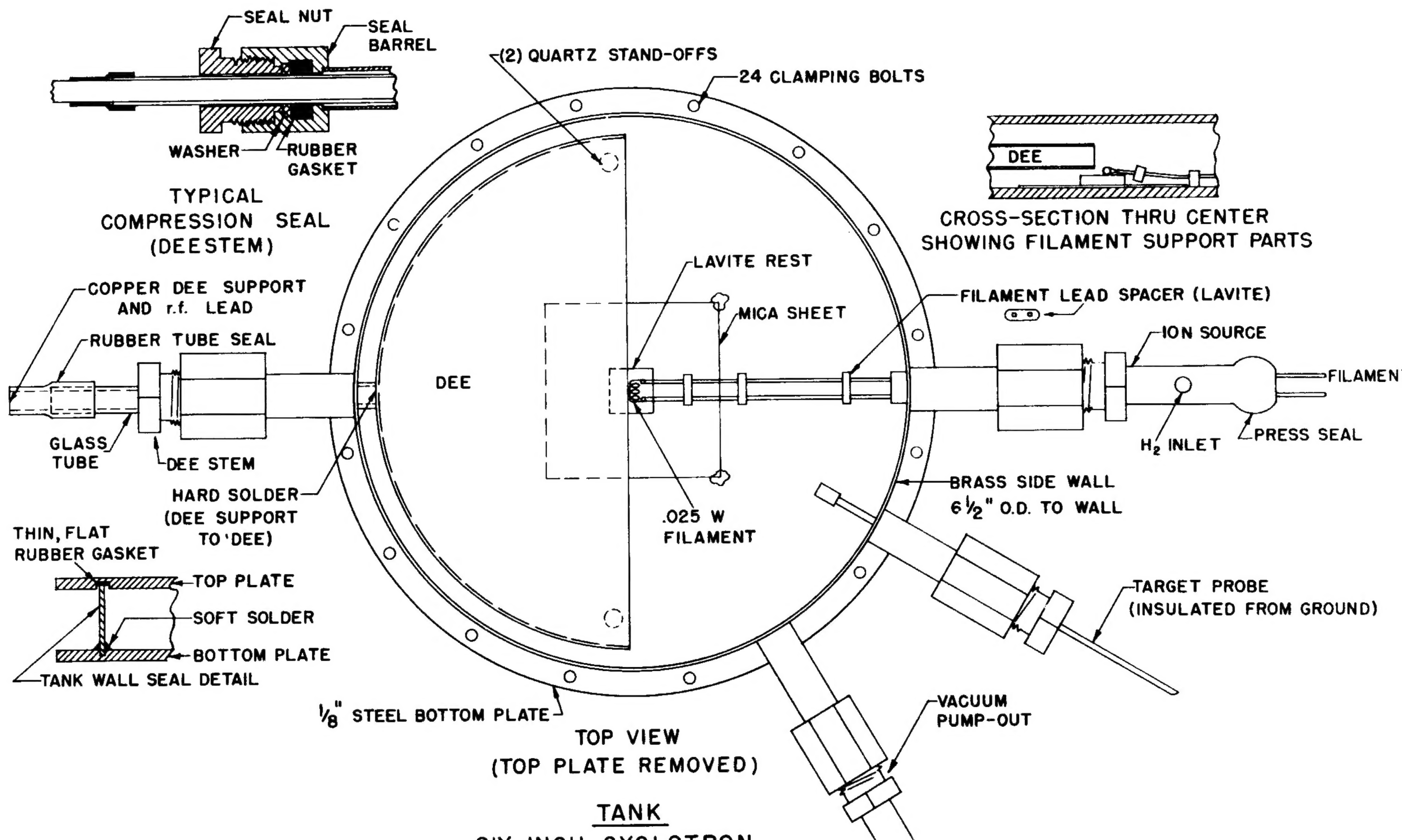
FIG. 1



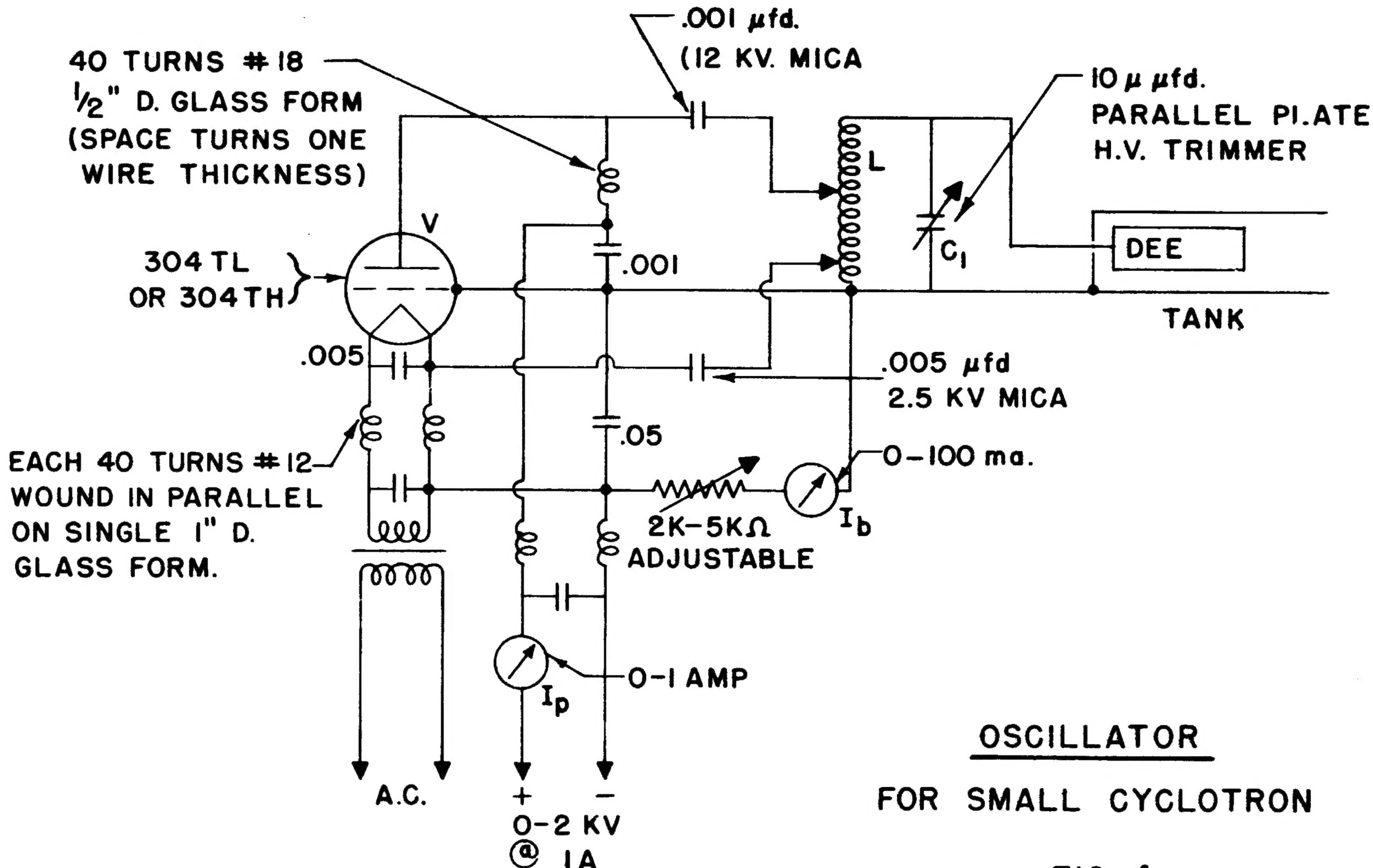
MAGNET

SIX INCH CYCLOTRON

FIG. 2



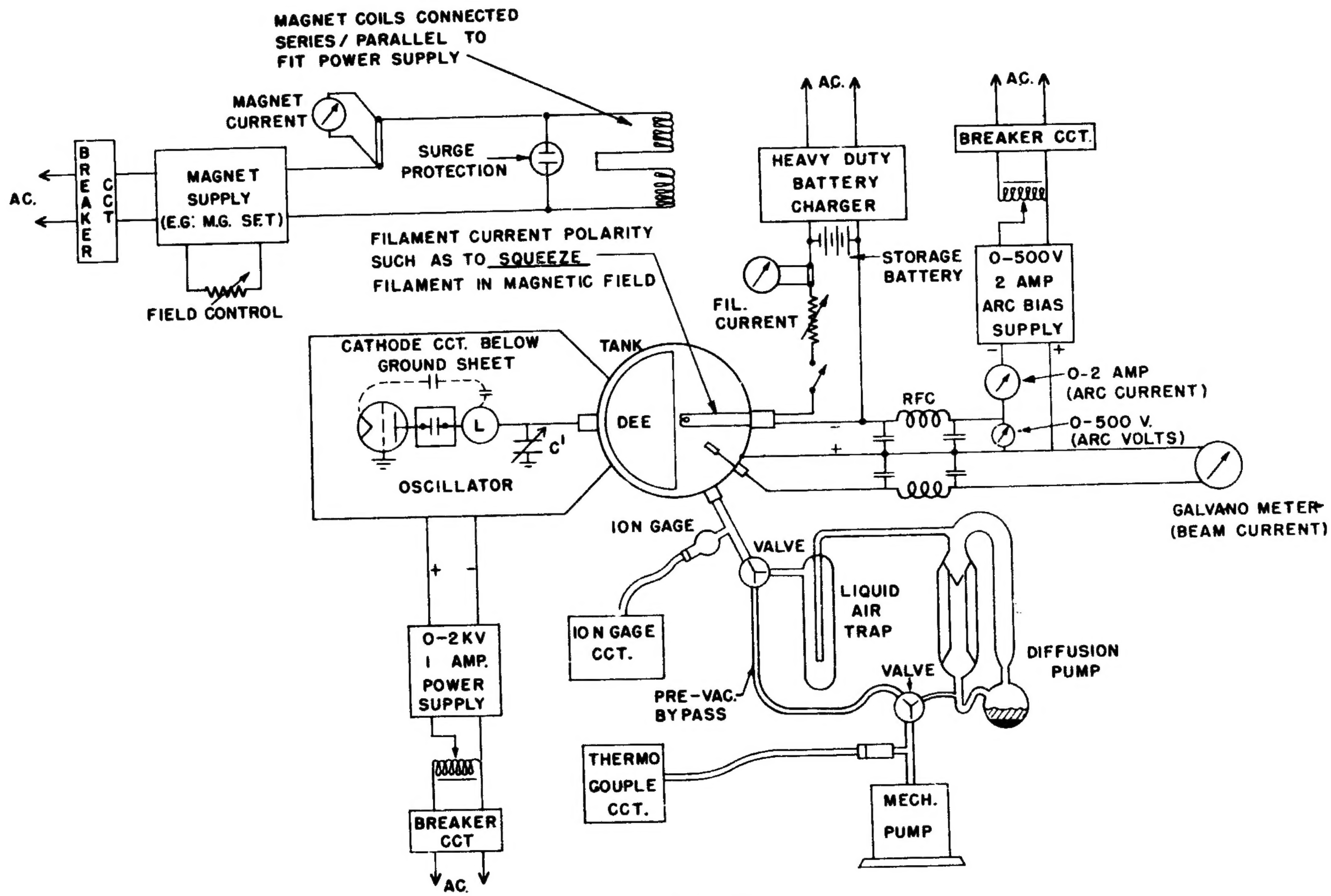
TANK
SIX INCH CYCLOTRON
FIG. 3



<u>OSCILLATOR</u>

FOR SMALL CYCLOTRON

FIG. 4



SCHEMATIC LAYOUT
CYCLOTRON CIRCUIT COMPONENTS

FIG. 5